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REPORT

The design of the prototype LS 5/9 studio monitoring loudspeaker

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Summary

The prototype of a new medium-power studio monitor is described which is physically small enough to be accommodated in areas where a large high-power monitor would be inappropriate.

The main design and performance features are as follows: - A vented cabinet having a volume of 28 litres (1 cubic foot). Two drive units; a proprietary 34mm soft-domed high frequency unit and a BBC-designed 200mm low-frequency unit having a polypropylene diaphragm and a high temperature voice-coil. A low-level cross-over circuit feeds a 50 watt stereo amplifier which drives the units separately; the cross-over frequency is 2.4 kHz. The axial frequency response is ±3 dB from 56 Hz to 16 kHz and the maximum sound level is 100 dB(A) at 1m on axis measured in a typical listening room using light music.

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Section	Title	Page
	Summary	Title Page
1.	Introduction	1
2.	General design considerations	1
3.	Drive units	2
	3.1. Low-frequency drive unit type LS 2/14	2
	3.2. High-frequency drive unit	3
4.	Cabinet	3
5.	Frequency splitting and equalisation	4
6.	Appraisal of design	6
	6.1. Subjective quality	6
	6.2. Maximum sound pressure level	7
	6.3. Power handling	8
	6.4. Stereo image width	8
7.	Conclusions	8
8.	References	8

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1. Introduction

Sound quality assessment and balancing of programmes is normally carried out using high-quality monitoring loudspeakers which are physically large because of the need for an extended low-frequency response. There is also a requirement to reproduce sound at high levels in order to be able to fulfil the complete range of requirements which include both 'pop' and serious music.

The recent studio monitoring loudspeaker, the LS 5/8[1], has a cabinet volume of 109 litres (3.9 cubic feet) and its size therefore makes it inappropriate for use in many small areas where its high sound level capability is not required. In small control cubicles, outside broadcast vehicles and outside broadcast locations to which loudspeakers have to be transported, use is frequently made of much smaller loudspeakers. In the past such areas have used LS 3/6 and LS 3/5A[2] types which have cabinet volumes of 50 litres and 5 litres (1.8 and 0.18 cubic feet) respectively. The need for improved sound quality and higher sound power than is available from either of these two small types led to the the request for a new design.

2. General design considerations

The design of the prototype LS 5/9 monitor*, see Fig. 1, was based on the following requirements.

1. Small cabinet size with a maximum volume of 28 litres (1 cubic foot). This is intermediate in size between the LS 3/6 and the LS 3/5A types, enabling it to be used in most areas.

2. The ability to reproduce sound levels of 100 dB(A) measured on axis 1m in front of the loudspeaker in a typical listening room for all types of programme material other than 'pop' music.

3. The use of two driver units to simplify the frequency splitting† between the units.

4. The high-frequency driver unit to be of the same type as is used in the LS 5/8 monitor.

5. The reproduced sound quality to have a low level of coloration* and to match as closely as possible that of the LS 5/8 monitor.

6. The 200mm low-frequency drive unit to be an in-house design which makes use of the materials, techniques and experience gained from the work done on the 300mm low-frequency drive unit for the LS 5/8 monitor.

7. The ability to produce a sharply defined stereo image.

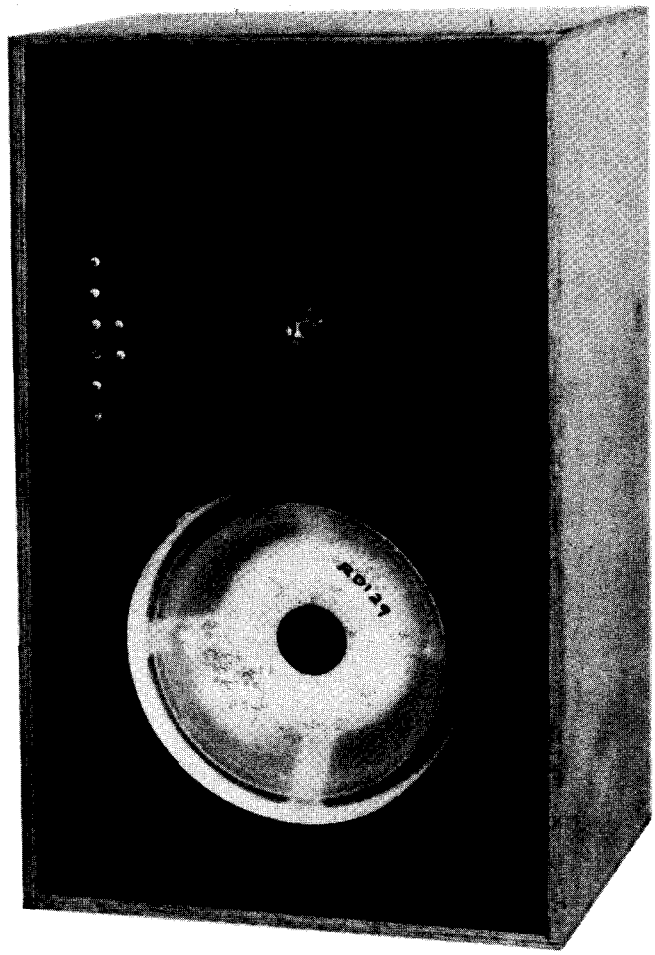


Fig. 1 — Prototype small monitoring loudspeaker type LS 5/9 with front grille removed.

* Throughout this report the term 'monitor' is used to describe a monitoring loudspeaker.

† The term 'frequency splitting' is normally used but a more accurate term would be 'band splitting'.

* The term 'coloration' is used in this Report to describe tonal effects which, although clearly audible, do not usually show up in steady-state measurements. They are believed to be due to mechanical resonances in the drive units.[3]

3. Drive units

3.1. Low-frequency drive unit type LS 2/14

A successful in-house design of a low-frequency drive unit was developed for the LS 5/8 high level monitor. This 300mm unit, designated LS 2/11, used materials and techniques which were considered to be appropriate for use in the design of a 200mm drive unit, designated LS 2/14, for the LS 5/9.

The principal feature of the design of the LS 2/11 unit is the use of polypropylene for the diaphragm material; polypropylene is a mechanically lossy material which probably accounts for the low level of coloration. The material is also light in weight (specific gravity = 0.9) and, because it does not require the addition of a surface damping layer, the unit has a low moving mass. This in turn results in an increase in sensitivity of about 4 dB when compared with units having a cone made from Bextrene (a rubberised polystyrene which requires an additional damping layer applied to the surface). The LS 2/11 diaphragm surround is made of thin plasticised PVC which gives a light and compliant termination for the cone. This, combined with a compliant spider, maintains a low resonant frequency for the moving system. The LS 2/14 unit makes use of all these features and gives a 200mm unit which is superior in a number of respects to any other units in current use.

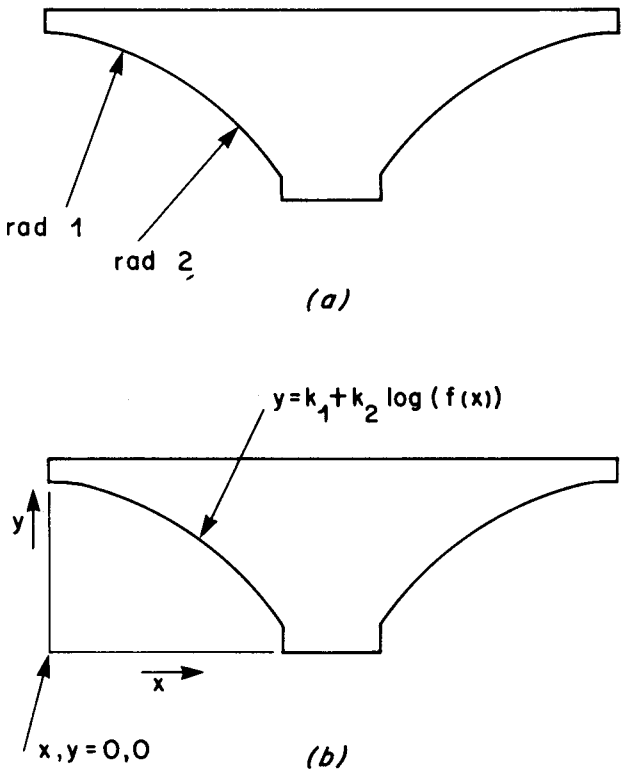


Fig. 2 – Profile of 200mm drive unit diaphragm mould (a) Profile 1 (b) Profile 2.

The exact relationship between the shape of the diaphragm of a drive unit and the sound quality reproduced by it is not known and because of this the diaphragm shape at first chosen for the LS 2/14 was one produced from an existing mould. This mould, designated profile 1 (Fig. 2 (a)), had been successfully used previously to produce diaphragms for the LS 2/6 Bextrene drive units used in the LS 3/6 monitor. The profile is essentially a dual radius form, with a smooth transition between the two radii of curvature.

A number of drive units were manufactured with polypropylene diaphragms using the profile 1 mould and listening tests suggested that the sound quality was excellent. However, the unequalised response/frequency characteristic plotted in Fig.3 (a) exhibits a dip in the region around 350 Hz which was found, using laser interferometry,[4] to be associated with the edge of the diaphragm flapping because of a lack of axial rigidity. Presumably this effect was less important when the diaphragm was moulded from the more rigid Bextrene material.

To improve the axial rigidity and thereby to reduce or eliminate the dip in the response/frequency characteristic a new mould was designed. This mould has a profile based on a logarithmic function which gives a more nearly constant stiffness over the whole area of the cone. This mould is designated profile 2 and is shown in Fig. 2 (b). A typical unequalised response/frequency characteristic of a unit made with a diaphragm moulded to profile 2 is shown in Fig. 3 (b). A comparison with Fig. 3 (a) showns that the dip at 350 Hz has been eliminated. Listening tests showed that the sound quality of the profile 2 unit was also excellent. There are other real differences between the response/frequency characteristics but none of these seemed to be related to any audible differences and therefore they were not investigated further.

Using several samples of the two types of unit further listening tests were carried out, the results of which showed a slight preference for the sound quality of the profile 1 units, in spite of the step at 350 Hz, and therefore further development was concentrated on this type. Subsequently a number of problems arose which were directly attributable to the lack of axial rigidity exhibited by profile 1 diaphragms. It was found that over a period of time which varied from days to months there was a distortion of the shape of

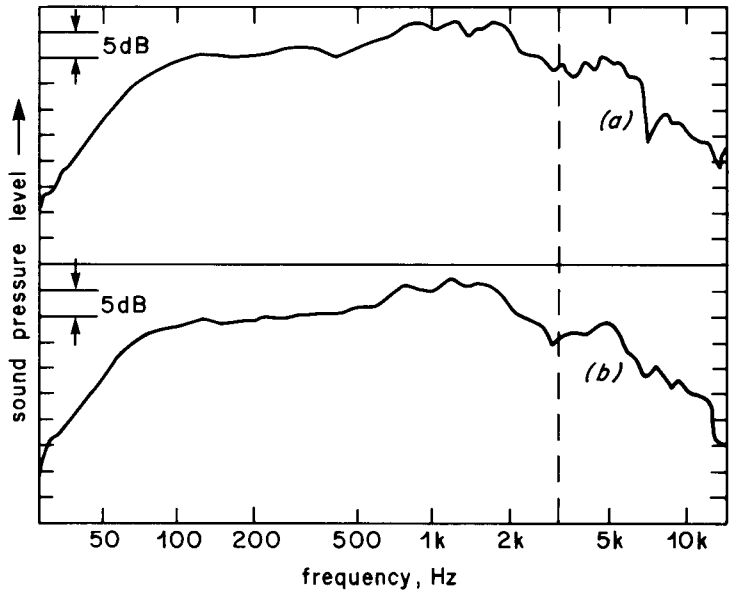


Fig. 3 — Unequalised response/ frequency characteristic of LS 2/14 unit (a) Profile 1 (b) Profile 2. Note: At frequencies above about 3 kHz the cross-over circuitry rapidly attenuates the output from the LS 2/14.

the diaphragm at its periphery. The time of onset and magnitude of this mechanical distortion were determined by the precise temperature of the material and mould during the vacuum forming process and the depth and frequency of the dip in the response was highly variable. In addition a comparison of the harmonic distortion produced by the two types of unit showed that the harmonic distortion produced by the profile 1 units was considerably greater than that produced by the profile 2 units, as shown in Fig. 4. (overleaf). The problems associated with the profile 1 diaphragms were further exacerbated when later samples of polypropylene were obtained which were less rigid than the earlier sample because the formula for the granules from which the sheet was formed had been altered by the manufacturer. A decision was therefore made to use profile 2 despite the slight preference for the sound quality associated with the earlier profile 1 units. Fig. 5 (overleaf) shows a complete LS 2/14 unit using profile 2.

To enable the LS 5/9 to produce a sound pressure level (SPL) of 100 dB(A), a large diaphragm excursion is necessary at low frequencies and consequently a long voice coil is also necessary if it is to remain in the magnetic field. However by the use of a vented cabinet the diaphragm excursion can be considerably reduced for the same reproduced sound pressure level at, and near to, the vent resonance frequency.

Large electrical signals are required to drive the unit fully and in order to enable the voice coil assembly to cope with the power dissipated, high temperature materials have been chosen and are the same as those used for the LS 5/8 voice coil assembly[1]. A high flux-density magnet was also chosen to enhance further the sensitivity of the unit.

3.2. High-frequency drive unit

The high-frequency drive unit is a commercially-made 34mm diameter soft-domed unit with a high flux-density magnet; it is designated type LS 2/12 and is identical to the unit used in the LS 5/8 monitor. This choice was made for reasons of standardisation and to assist with the sound quality match between the LS 5/9 and the LS 5/8. Clearly, the power handling capacity of the unit must be adequate when used in the LS 5/9 since it has proved to be satisfactory for the higher powered LS 5/8.

4. Cabinet

The development of the LS 2/14 unit was carried out using a cabinet volume of 56 litres (2 cubic feet). This cabinet was demountable to enable quick substitution to be made of different units for their assessment both subjectively and objectively. The final choice of 28 litres (1 cubic foot) for the cabinet volume was made because of the operational advantages of smaller size and weight albeit at the cost of one-quarter of an octave in the bass response when compared with a 56 litres (2 cubic foot) size cabinet. As already mentioned a vented cabinet design was chosen to reduce the bass unit diaphragm excursion at resonance.

Figure 6 (overleaf) shows the dimensions of the cabinet and baffle. The panels are made of 9mm birch plywood. The resonant modes of the panels are damped with self-adhesive bitumen-based damping pads applied to all inside surfaces except

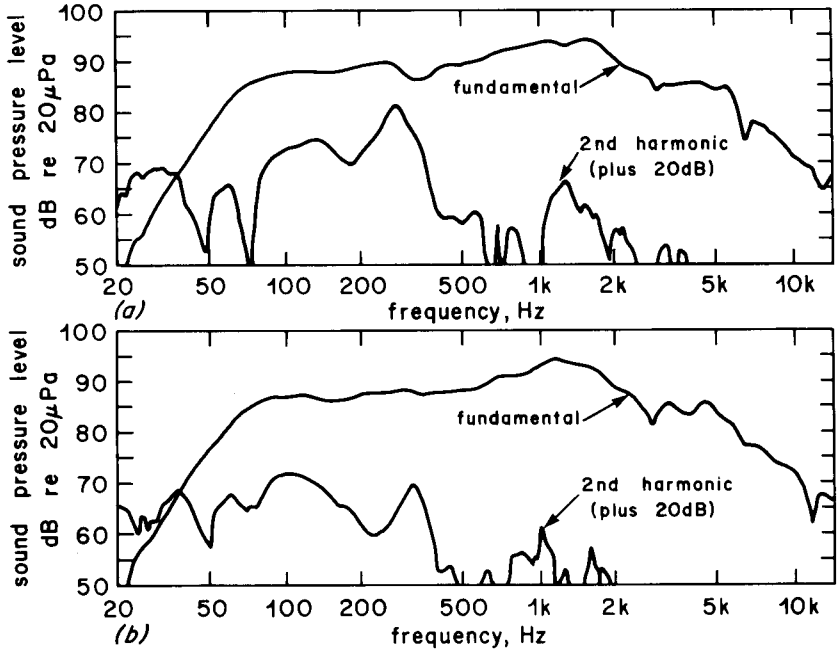


Fig. 4 — Comparison of 2nd harmonic distortion of LS 2/14 unit measured in free field room with constant 2 volts r.m.s. applied to voice coil. (a) Profile 1, (b) Profile 2.

Note: For ease of presentation the gain of the 2nd harmonic distortion plot has been increased by 20 dB relative to the fundamental plot.

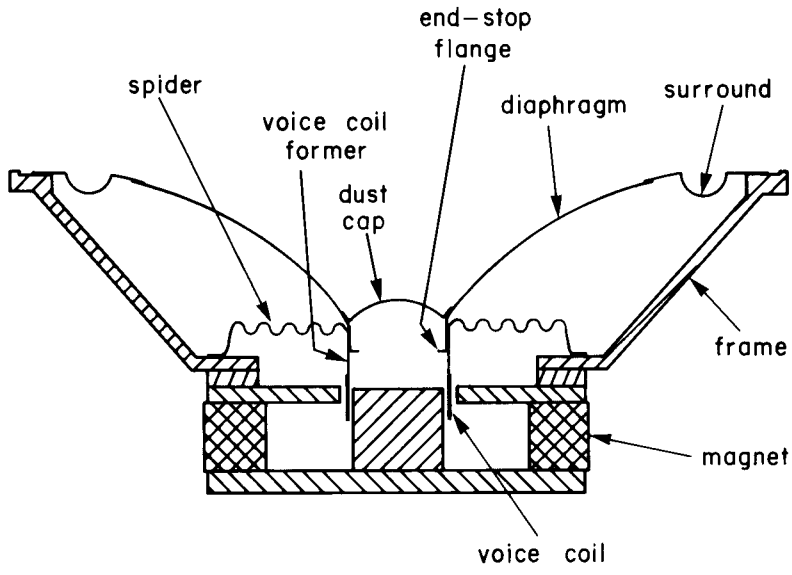


Fig. 5 — Prototype 200mm loudspeaker drive unit, type LS 2/14.

for the front baffle to which the drive units are affixed. The internal standing-wave modes of the cabinet are damped by slabs of mineral wool attached to the internal surfaces on top of the panel damping treatment. These slabs are enclosed in 100-gauge polythene bags which prevents the escape of any loose fibres without affecting significantly the acoustic absorbing property of the mineral wool over the frequency range of interest.

5. Frequency splitting and equalisation

During the development stage of a monitoring loudspeaker when frequent changes in the frequency splitting and equalisation circuitry (commonly referred to as the crossover circuitry) may be required, it is advantageous to use an active, low-level system because of the ease of adjustment. In particular, under these circumstances no account need be taken of any variation of drive unit impedance. A block diagram of the crossover circuit is shown in Fig. 7 (opposite). In addition to the frequency splitting at 2.4 KHz, in order to obtain a flat response/frequency characteristic, low-frequency equalisation and a dip circuit are required for the low-frequency unit. These requirements are very similar to those of the LS 5/8 and, consequently, use was made of the circuitry designed for the latter with suitable component value modifications. The circuitry drives the separate channels of a commercial 50 watt stereo amplifier. Fig. 8 (overleaf) shows

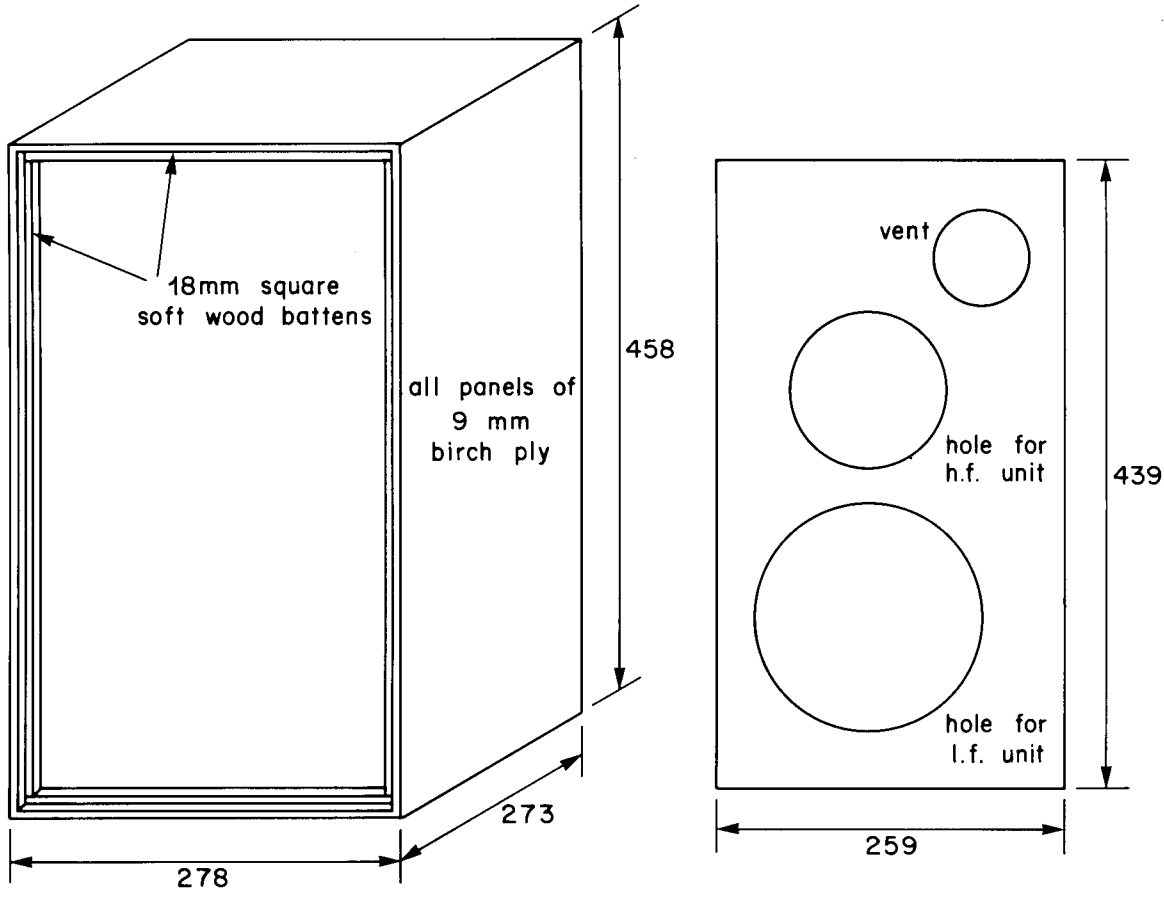


Fig. 6 – LS 5/9 Cabinet and baffle.

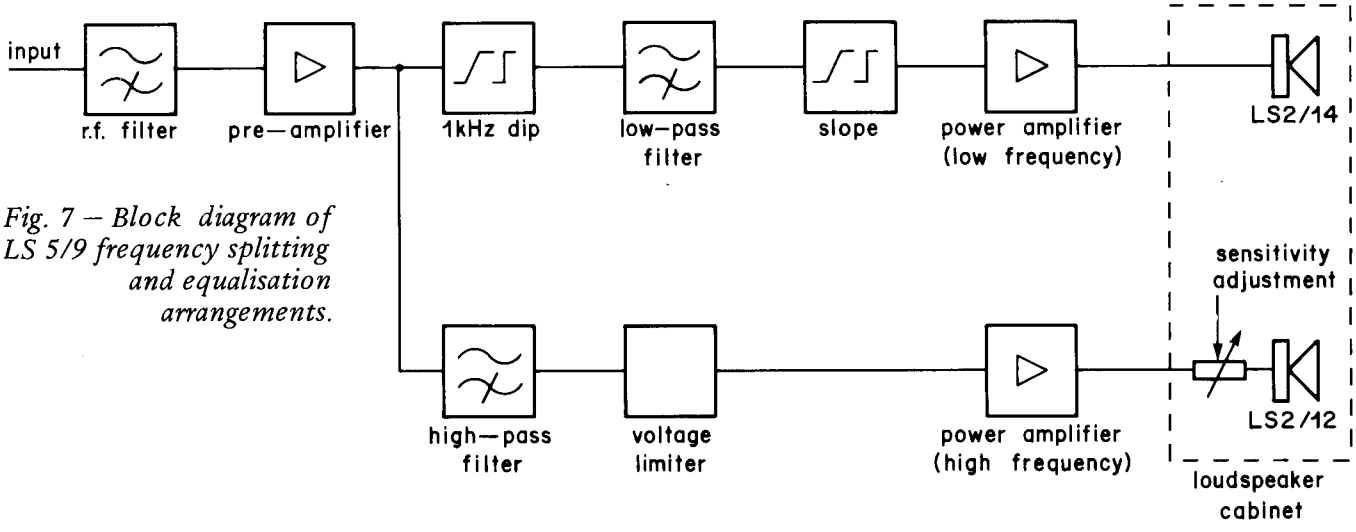


Fig. 7 – Block diagram of LS 5/9 frequency splitting and equalisation arrangements.

the unequalised response/frequency characteristic of the two drive units when driven from a constant voltage source and Fig. 9 (overleaf) shows the response/frequency characteristic of the crossover circuitry. The shallow dip at 1 kHz in the response of the low-frequency part of the crossover circuit is seen to correspond with a broad peak in the unequalised response of the LS 2/14 unit, and has been found to give a subjective improvement in quality.

The high-frequency part of the crossover circuit includes a means of restricting the voltage fed to the high-frequency channel of the power amplifier in order to limit the power output to within the rated value of the drive unit. Adjustment for

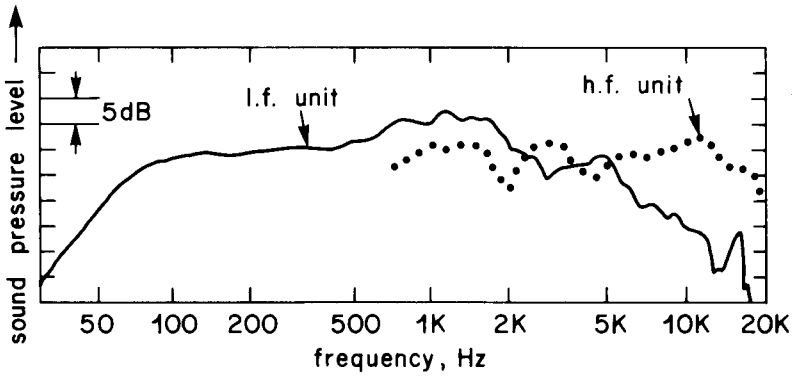


Fig. 8 — Unequalised response/ frequency characteristic of LS5/9 drive units driven at constant voltage.

Fig. 9 — Response/frequency characteristic of frequency splitting and equalisation circuitry for prototype LS 5/9.

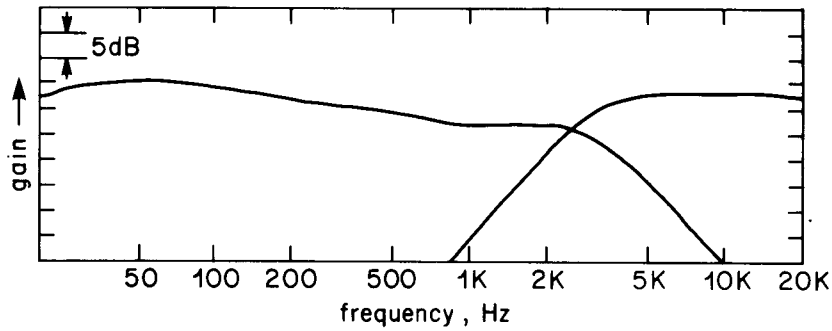
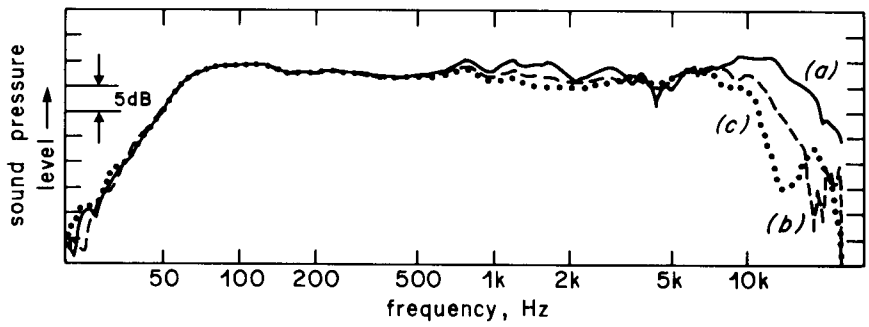


Fig. 10 — Response/frequency characteristic of prototype LS 5/9 measured in free field room at 1.5 m. (a) on axis (b) 30° off axis horizontally (c) 45° off.



variation in the relative sensitivity of the low-frequency and high-frequency drive units is achieved by including a series resistor network between the power amplifier output and the high-frequency drive unit. The resistor network is mounted on the front baffle and enables an adjustment of ±3 dB in ½ dB steps to be obtained.

The overall response/frequency characteristic of the LS 5/9 with its crossover circuitry is shown in Fig. 10. These measurements were made in the free field room at a distance of 1.5m and the response is shown for three directions relative to the axis of the high-frequency unit. The plot shows some variation in response in the 1 - 3 kHz region i.e. in the region of the crossover frequency and where the response of the low-frequency unit becomes directional. The response variations above 8 kHz are to be expected because of the directivity of the high-frequency unit. Furthermore the precise equalisation provided over this band can only be obtained by field-trial evaluations currently being carried out.

Finally it is worth noting that although the prototype LS 5/9 design uses a low-level active crossover circuit it may be economically advantageous to use a high-level passive crossover circuit for a production version.

6. Appraisal of design

6.1. Subjective quality

Extensive listening tests have shown that the sound reproduced by the prototype LS 5/9 monitor is less coloured than that of any similarly sized loudspeaker in current use by the BBC and that the match in overall sound quality between the LS 5/9 and the LS 5/8 is very good. Clearly the match at the bass end of the frequency spectrum where the LS 5/8 is extended by one

half-octave compared with the LS 5/9 will always be imperfect. A comparison of the bass response of the LS 5/9 and LS 5/8 is shown in Fig. 11 However the excellence of the match is demonstrated particularly well on male speech which provides a very stringent test of tonal quality. In this case the extended bass response of the LS 5/8 is not very evident because of the restricted content of male speech at this end of the frequency spectrum.

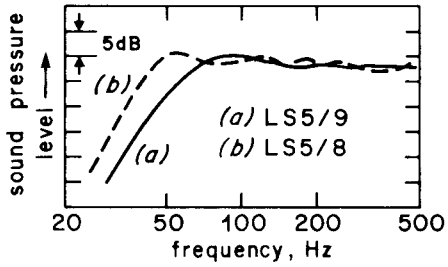


Fig. 11 — Comparison of bass response.

6.2. Maximum sound pressure level

There are several ways of measuring the sound pressure level generated by a loudspeaker. The results will depend upon the type of signal used, the environment in which the loudspeaker is placed and the measurement units employed.

Comparison of the performance of the LS 5/9 and LS 5/8 was made in two ways. Firstly, measurements of sound pressure level were made at discrete frequencies using a precision sound level meter placed at a distance of 1m in front of the loudspeaker in a free-field room. Pure tone signals centred at one-third octave intervals were fed to the loudspeaker with the high-frequency unit disconnected. The output level was then adjusted for each frequency until the 2nd harmonic distortion of the reproduced signal reached 5%. At and below 250 Hz the distortion was produced by the loudspeaker bass unit, whilst above 250 Hz the distortion was due to the drive amplifier clipping. Fig. 12 shows the sound pressure levels measured for the two types of loudspeaker, the mean difference between the curves is 9 dB. The peaks at 80 Hz and 50 Hz correspond approximately to the vent resonance frequency of the LS 5/9 and LS 5/8 cabinets respectively.

A further comparison of performance between the LS 5/9 and the LS 5/8 is shown by a measurement of equivalent loudness, as defined by the L_{eq} *. This is the equivalent continuous 'A' weighted sound pressure level, of each

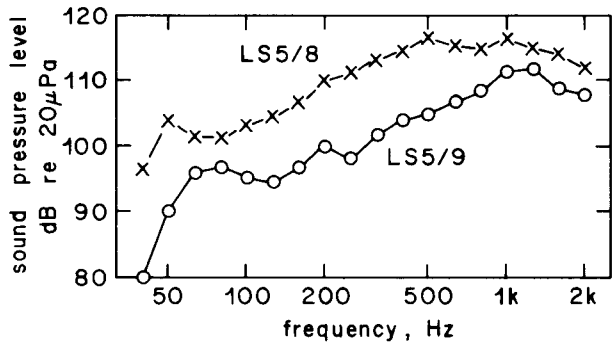


Fig. 12 — Maximum sound pressure levels produced in free-field room at 1m for 5%. 2nd harmonic distortion using pure tone excitation.

Note: High-frequency unit not connected.

loudspeaker type when reproducing programme. The choice of programme should be such that the test of performance is stringent and at the same time appropriate to the use for which the loudspeaker is designed. Programme having a high level content at low frequencies, such as some 'pop' music[5], will restrict the maximum level at which programmes can be reproduced and is thus not appropriate. The programme chosen for this comparison was a typical example of light music. This was reproduced in a listening room of volume 70m^3 and an average reverberation time of 0.27 seconds.

The loudspeaker output level was adjusted to reproduce the maximum sound level attainable prior to the onset of audible distortion occurring on the low-frequency peaks. A precision sound level meter was placed at a distance of 1m in front of the loudspeaker and the 'A' weighted audio output was fed to a noise-dose meter from which the L_{eq} value was derived. A further measurement was made of the peaks of sound pressure as read on the sound level meter switched to the linear mode. The results of these measurements for the same programme item are shown in Table 1. (overleaf)

In each case the difference in performance between the LS 5/9 and the LS 5/8 is 8 dB which is near to the mean difference of 9 dB between the curves shown in Fig. 12.

$$*L_{eq} = 10 \log_{10} \left\{ \frac{1}{T} \int_0^T \left[\frac{P_{A(t)}}{P_o} \right]^2 dt \right\}$$

where T is the measurement period, P_o is the reference pressure of 20μP_a and $P_A(t)$ is the 'A' weighted instantaneous sound pressure.

Table 1

Comparison of sound pressure levels of LS 5/9 and LS 5/8 loudspeakers.

Loudspeaker type	L_{eq}, dB(A)	SPL, dB_{LIN}
LS 5/9	100	106
LS 5/8	108	114

6.3. Power handling

The power handling capability of the LS 2/14 unit was assessed by driving two units continuously over an extended period. The units were mounted in cabinets and driven from 50 watt amplifiers fed from the crossover circuitry. The programme source was BBC Radio 2 (light popular music with continuity speech) and the output level was adjusted to the point at which waveform clipping of the amplifiers was just occurring. The units failed after 32 days and 47 days respectively and both failures were due to excessive heating of the voice coils. It is therefore considered that in normal use the LS 2/14 unit is almost indestructible when fed from a 50 watt amplifier.

6.4. Stereo image width

The assessment of the stereo image width of the LS 5/9 was made using the same technique as that employed for the LS 5/8[1]. A series of subjective tests were carried out in which participants measured the apparent width of a central image produced by monophonic male speech when reproduced by a pair of LS 5/9s. The position of one edge of the image was assessed and was then moved electrically by a differential attenuator until it was coincident with a vertical tape which marked the geometrical centre between the loudspeaker positions, this was repeated with the other edge. From a knowledge of the relationship between image position and the level difference between the signals fed to the pair of loudspeakers[6] the subjective image width was derived. The stereo image width using this method was 320mm which is slightly greater than the width of the cabinet. This compares with a figure of 450mm for the LS 5/8 which is approximately the same as the width of the LS 5/8 cabinet. The above assessments were made in a listening room in which particular attention had been paid to the acoustics. Further tests should obviously be carried out in control rooms in which the acoustic conditions are less than excellent in order to determine the sharpness of the stereo image in conditions more likely to be met with in practice.

7. Conclusions

Using a new BBC designed low-frequency drive unit together with a commercial high-frequency drive unit, a successful prototype small-sized (1 cubic foot) high-quality monitoring loudspeaker has been designed. It is suitable for balancing a wide range of programmes at fairly high loudness levels in areas where a large high-power monitor is not suitable because of constraints on size.

Although results of field trials to date have been most encouraging, further assessments of prototypes of the production version need to take place and may lead to modifications of the design.

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